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Experimental Evaluation of the Effect of Compaction on the Behavior of Geosynthetics-Reinforced Pile-Supported (GRPS) Embankment System

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ABSTRACT

This article presents the results of two large-scale physical model studies of a geosynthetic-reinforced pile-supported embankment system (GRPS) under working stress conditions. The tests were performed at the Geotechnical Laboratory of the Federal University of Rio de Janeiro, COPPE/UFRJ, and simulate a GRPS construction under the plane-strain conditions. A backfill is composed of granular well-graded material and surcharge is applied by a pneumatic load system. A hydraulic platform elevator system simulates the soft soil settlement. For soil compaction, two different types of hand-operated compactors were used: a vibrating plate and a vibratory tamper. Equivalent vertical stresses for the vibrating plate (referred to as the “light compactor”) were much lower than the corresponding value of the vibratory tamper (referred to as the “heavy compactor”). The two models were similar, except for the induced stress due to compaction operation. In the first model, the vibrating plate was only used for backfill compaction. In the second model, the vibrating plate and the vibratory tamper were employed for the compaction of the backfill. The models were assembled and instrumented to monitor the transference of load between the soil, pile caps, and reinforcement. Settlements mobilized tensions on the reinforcement and the total stress at the interface between the pile caps and soil were measured. The results highlight the effect of the compaction induced stress on the behavior of GRPS.

KEYWORDS: geosynthetic-reinforced pile-supported embankment system, soft soil, physical model, arching effect.

1. INTRODUCTION

Geosynthetic-reinforced pile-supported embankment systems (GRPS) is a single or multi-layer reinforced composite structure made of earth and geosynthetic. In this technique, part of the soil weight above the geosynthetic is transmitted to the piles embedded on competent layers, minimizing post-construction settlements and avoiding soft soil instabilities.

Field monitoring data of GRPS (e.g., Spotti, 2006; Almeida *et al.*, 2007; Van Eeklen *et al*., 2014), several experimental studies were carried out in centrifuge tests (e.g., Hartmann *et al.*, 2014; Blanc *et al.*, 2013; Fagundes, 2016) and others small-scale models (e.g., Low *et al*., 1994; Demerdash, 1996; Horgan and Sarsby, 2002; McGuire, 2011; Van Eekelen *et al.*, 2012a) have been performed in order to evaluate the transference of load between the soil, pile caps and reinforcement. Few large-scale physical models of GRPS were noticed on literature (e.g., Chen *et al*, 2016; Dieguez *et al*, 2018).

1.1 Large-scale Physical Model of GRPS

Dieguez *et al* (2018) performed a large-scale physical model of a GRPS under working stress conditions (Figure 1) constructed at the Geotechnical Laboratory of the Federal University of Rio de Janeiro - COPPE/UFRJ to assess the transference of load between the soil, pile caps and reinforcement. In those models, induced settlements were applied under the geosynthetic reinforcement by moving downward a hydraulic platform elevator system, simulating the soft soil settlement. Two different types of construction sequence was performed: in the first test, the platform was released before the surcharge application and in the second test, the platform was released after the surcharge. Settlements mobilized tensions along the reinforcement and the vertical stress at the interface between the pile caps and soil were monitored. Results have shown, irrespective of the difference in construction sequence, the vertical stresses above the pile caps were almost the same and reached the corresponding value of the summation of all vertical load acting at the entire surface of the model at the end of tests. Despite that were measured less settlement at the second test. Moreover, the settlements and reinforcement loads monitored in the two tests shows a correspondence between those measurements: Less settlement leads to less mobilized reinforcement load.

Herein, using the same prototype and facilities as Dieguez *et al* (2018), shown on Figure 2, intend to evaluate the behavior of two large-scale physical models constructed under similar conditions using two different hand-operated compactors: a vibrating plate and a vibratory tamper, also used by Ehrlich *et al* (2012) and Mirmoradi *et al* (2016), shown in Figure 3. The box of the physical model is a U-shaped reinforced concrete wall of 1.5 m height, 3.0 m length and 2.0 m width, closed with a stiff metal-face, well attached to the concrete structure by 50-mm-diameter bolts. The inner part of this box is covered with a lubricated system composed by a thin layer of PTFE (polytetrafluoroethylene - Teflon) grease in the middle of two sheets of PVC (polyvinyl chloride) geomembrane, with the purpose to assure no shear stress between soil and the lateral of the box. Those models were also well-instrumented to monitor the settlements, reinforcement load and the total stress at the interface between the pile caps and soil.

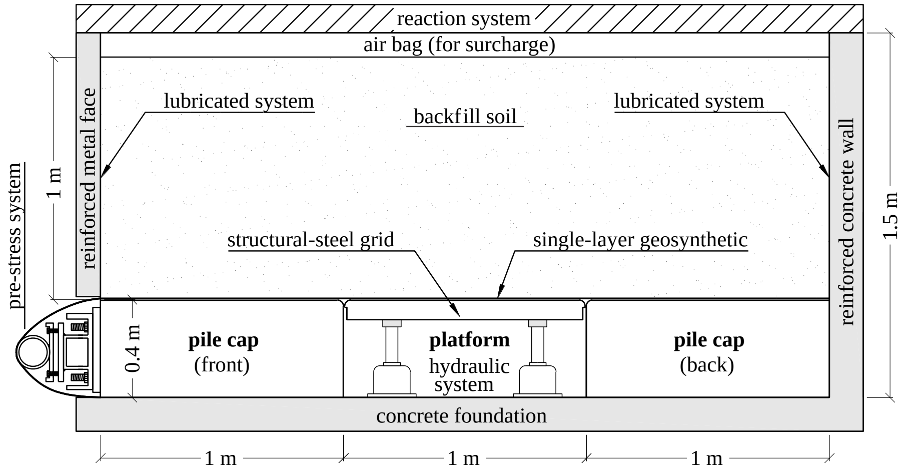

Figure 1. Cross-section of the physical model performed by Dieguez *et al* (2018).

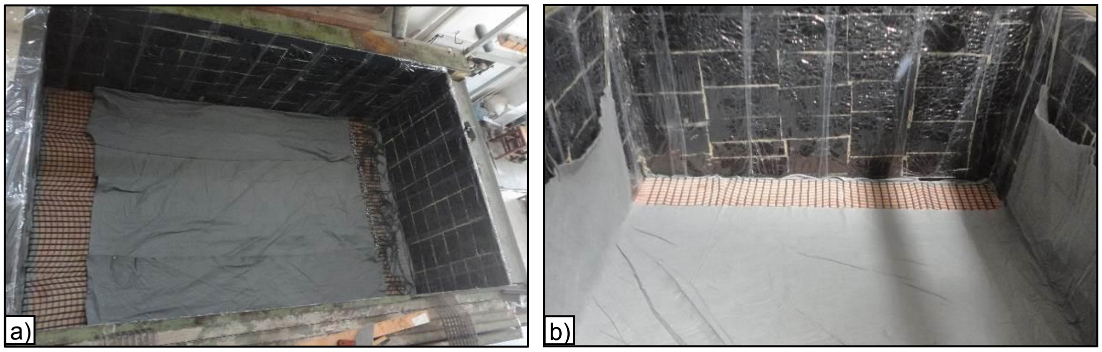

Figure 2. a) Top view of the reinforced concrete box and b) lubricated system (geomembrane and grease) performed by Dieguez *et al* (2018).

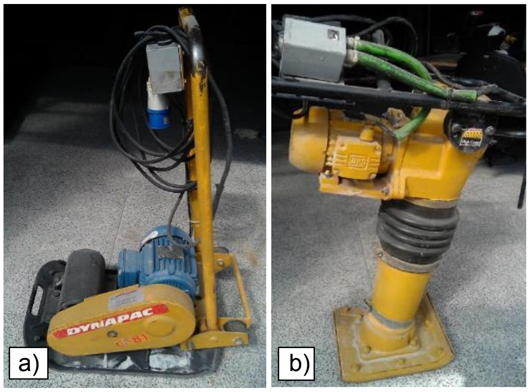

Figure 3. a) Light compactor, vibrating plate; b) heavy compactor, vibrating tamper (Mirmoradi, 2015).

2. EXPERIMENTAL PROGRAM

2.1 Reinforcement and Structures Material Properties

A uniaxial flexible PVA (polyvinyl alcohol) geogrid was used for the single-layer reinforcement and a very-thin sheet of geotextile to prevent the outgoing of the granular material. The physical and mechanical properties of this geosynthetic reinforcement was assessed by Dieguez *et al* (2019), performing wide-width tensile test under work-stress conditions with the strain-cell apparatus shown on Figure 4. No significant differences in the stiffness modulus was observed, when varying up to 10 times the strain ratio of the test. The stress-strain curves shows a relatively more stiff behavior in the initial range of stretch of the material, obtaining as the average of stiffness modulus equal to 2400 kN/m. The properties of the geosynthetic reinforcement used in the present study are shown in Table 1.

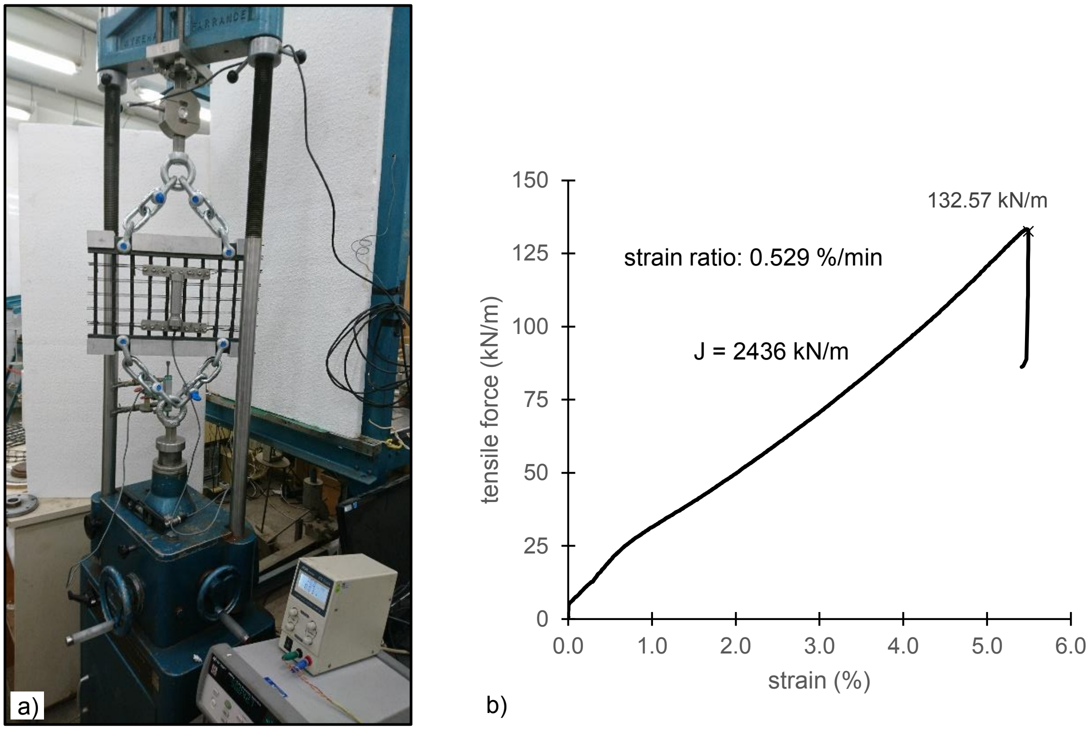

Figure 4. a) Wide-width tensile test on PVA geogrids, performed by Dieguez *et al* (2019) and b) ultimate strength and results of the stiffness modulus obtained for the geosynthetic used in the present tests.

Table 1. Mechanical and physical properties of the reinforcement (PVA geogrid).

Stiffness modulus J, (kN/m)	2400
Ultimate strength (kN/m)	133
Strain-ratio (%/min)	0.076; 0.254; 0.354; 0.529 ; and 0.685
Opening size, (mm)	30x30

The hydraulic platform (Figure 5a) consists in a metal grid composed by C-shaped structural beams sited above load cells and connected by chains at the corners to the concrete base. This system firmly moves the platform up or down; electric sensors connected to the jack monitored the vertical displacements (“settlements”) during the tests.

The pile caps were capable to resist horizontal and vertical stresses, monitoring vertical total stress using soil pressure transducer placed above it, as shown on Figure 5b. The structure were manufactured using high-stiff wood with negligible deformation along the level of stress applied over it.

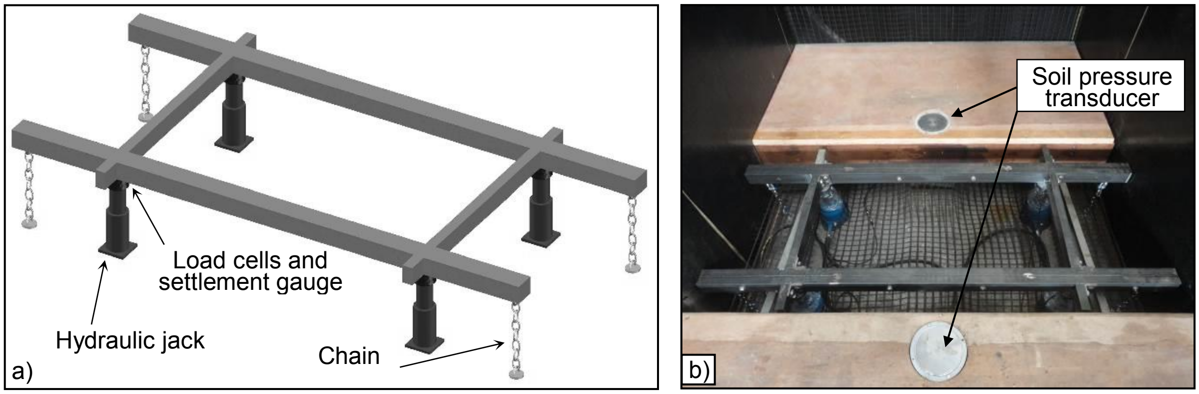

Figure 5. a) Schematic representation of the hydraulic platform system and b) the hydraulic platform mounted between the pile caps (Dieguez *et al* 2018).

2.2 Soil Properties

The backfill material of the physical model is manufactured sand (crushed quartz), also used by Saramago (2002) and Dieguez *et al* (2018). It has as main characteristics: to be well graded, hysteretic and purely frictional behavior. Plane-strain and axisymmetric triaxial tests in this soil were also performed by Souza Costa (2005), achieving a friction angle equal to 50º and 53º for the unit weight of compacted soil equal to 19 kN / m³ and 20 kN / m³, respectively. The highest friction angle corresponds to combining the vibratory plate and vibratory tamper (heavy compactor). The smallest friction angle obtained corresponds to the compaction made only with the vibratory plate (light compactor). Figure 6 shows the friction angle *versus* unit weight of soil correlation curves obtained by Souza Costa (2005) for axisymmetric or plane-strain triaxial using the crushed quarts soil. Table 2 summarize the properties for the soil, the same soil used as backfill in the present study.

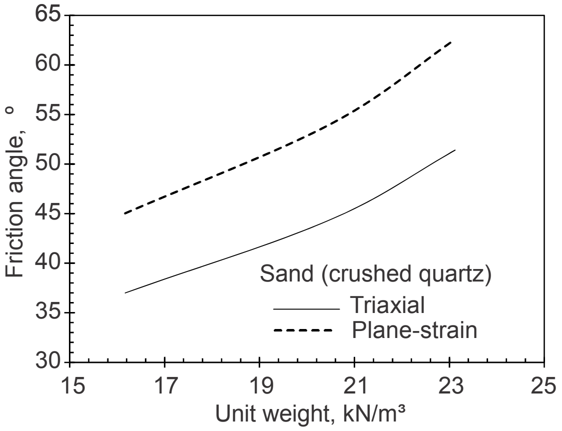

Figure 6. Friction angle *versus* unit weight of soil correlation curves for axisymmetric or plane-strain triaxial using the crushed quarts soil (Souza Costa, 2005)

Table 2. Mechanical and physical properties of the backfill soil (crushed quartz).

Soil Compaction **Type 1** (light compacted crushed quartz)	
Unit weight, (kN/m³)	19
Plane-strain triaxial friction angle (º)	50
Soil Compaction **Type 2** (heavy compacted crushed quartz)	
Unit weight, (kN/m³)	20
Plane-strain triaxial friction angle (º)	53

2.3 Instrumentation

Hydraulic settlement gauges (HSG) was placed in five points above the surface of the backfill soil and used for monitoring vertical displacements. Vertical total-stresses were monitored using three soil pressure transducer (TPT, total-pressure-transducer) located above the pile caps. Four strain-cells were connected to the geogrid to monitor the strain along the geosynthetic reinforcement during the test. Figure 7 shows a cross-section of all located instruments.

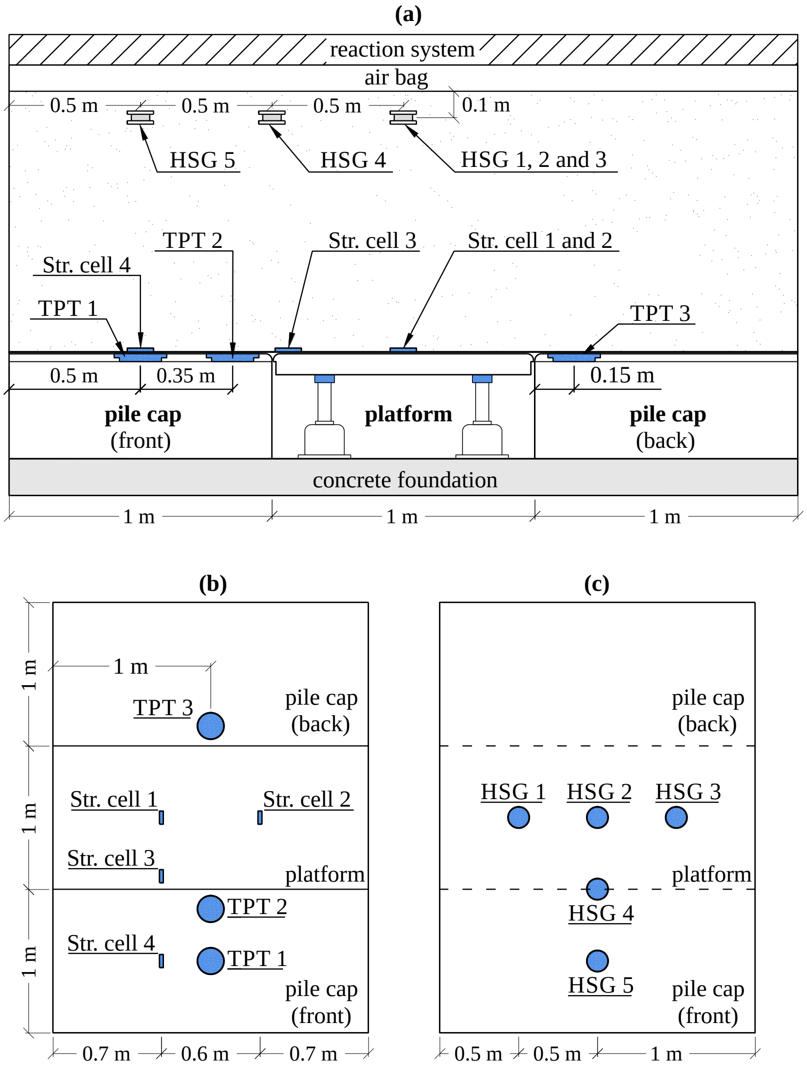

Fig.7 a) Cross-section of the model and b) scheme of the instruments position above the pile caps and platform and c) scheme of the instruments position above the backfill soil.

2.4 Construction Sequence and Surcharge

For the construction sequence and surcharge, the same procedure developed by Dieguez *et al* (2018) was used. Backfill construction was performed in five layers of soil, 0.2 m thick and placed dry. The sequence of construction were executed in two stages per layer of soil: placement of soil and compaction Type 1 or Type 2. In Type 1 compaction, the entire surface of the backfill is compacted by a mechanical process using the vibrating plate (light compactor) around 10 minutes, obtaining a soil unit weight after compaction equal to 19 kN/m³, corresponding to a less stiff soil structure. To obtain the compaction Type 2, another 10 minutes using the vibratory tamper (heavy compactor) was necessary to obtain a stiffer soil structure. Others physical models studies successfully tested this procedure of soil compaction, monitoring accelerometers installed in the body of the compactor equipment showed a constant digit magnitude after this 10-min period (Ehrlich et al, 2012; Mirmoradi et al., 2016).

Static surcharge up to 50 kPa was applied over the entire surface at the last layer of the backfill using an air bag with a reaction system. Surcharge increments were made every 10 kPa, gradually and not immediately until the 50 kPa pressure was reached. Stabilization of the monitoring instruments during the current pressure was ensured at each stage, before performing a further pressure increase. Figure 8 shows the surcharge system.

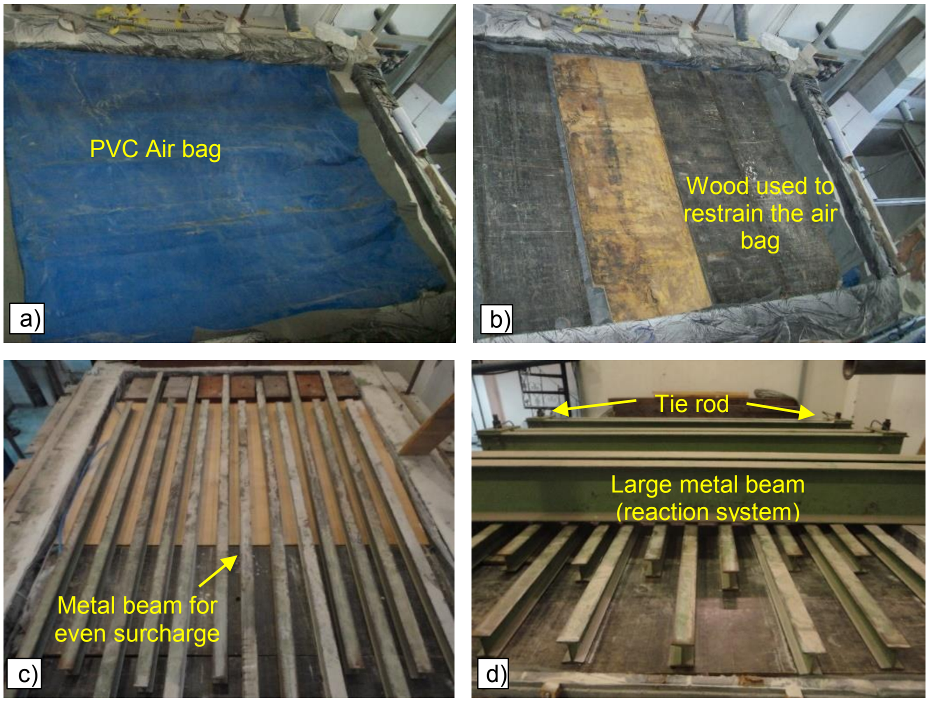

Figure 8. a) Air bag system, b) woods used to restrain the air bag, c) metal beams used to uniformed surcharge above and d) reaction system using a large metal beam attached to two tie rods.

3. ANALYSIS AND RESULTS

3.1 Reinforcement Load

Reinforcement load are estimated considering the measured strain and the stiffness modulus of the geogrid. Figure 9 shows for each compaction Type 1 and Type 2 the reinforcement load for different stages of tests. EOC represent the end of the backfill construction, and begin of the downward movement of the platform. EPR is the end of platform releasing (no more contact between the platform and the reinforcement). Surcharge application start after the stabilization of the EPR to the end of test.

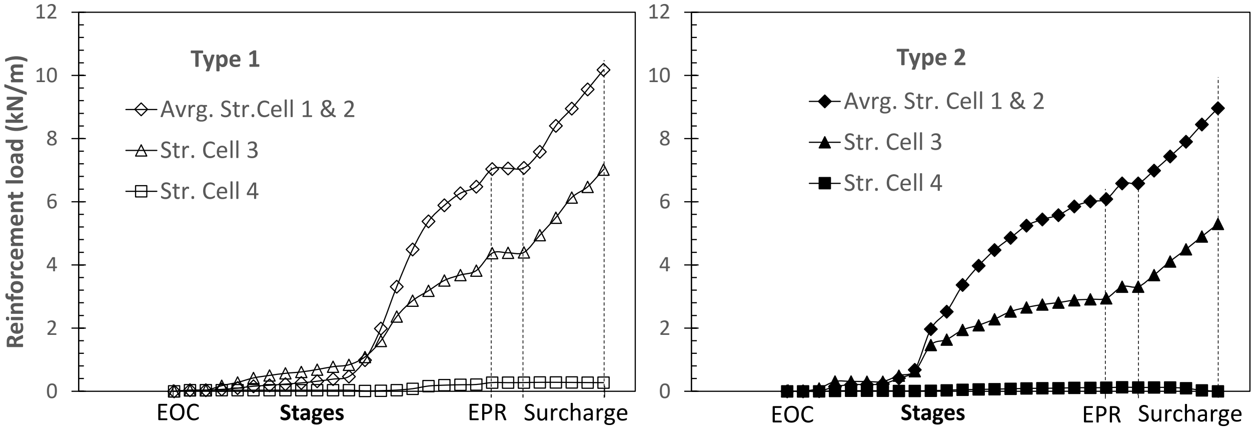

Figure 9. Estimated reinforcement loads for compaction Type 1 and Type 2.

3.2 Settlements Monitored Over the Surface of Backfill

Hydraulic settlements gauges (HSG) measurements are shown in Figure 10. For the middle transverse section of the physical model have plotted the average of HSG 1, 2 and 3. The results indicate higher settlements when the backfill was compacted only with the vibratory plate (Type 1) in agreement with the results obtained from the monitored loads on the geosynthetic reinforcement.

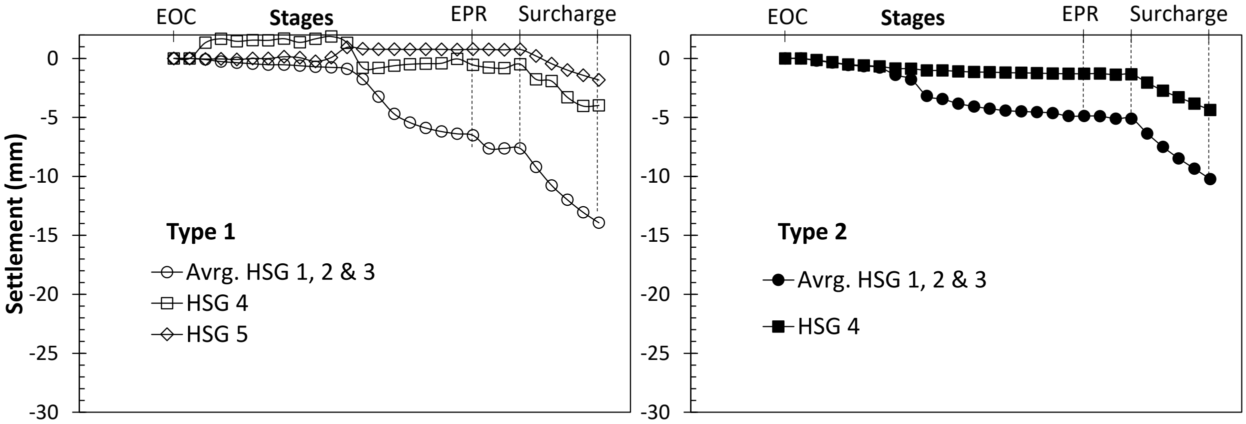

Figure 10. Measured settlements for compaction Type 1 and Type 2.

3.3 Vertical Load Monitored Above the Pile Caps

Vertical load above the pile caps are calculated considering the summation of the vertical component of the reinforcement loads and the monitored data of the TPT's installed at the edge and the center of the pile caps. Numerical modeling indicates that the redistribution of the vertical stress above the pile caps, due to the platform release, could be represented by a non-linear polynomial or exponential curve.

Figure 11 shows the measured and calculated values of load above the pile caps. For the theoretical determination of vertical load (upper and lower limit), it was assumed a uniform distribution of stress, derived from the self-weight of the backfill and the applied surcharge. In this case, upper and lower limit are calculated considering the load of soil mass and surcharge applied in the area of pile caps, only, and the total load in the area of pile caps and platform, respectively.

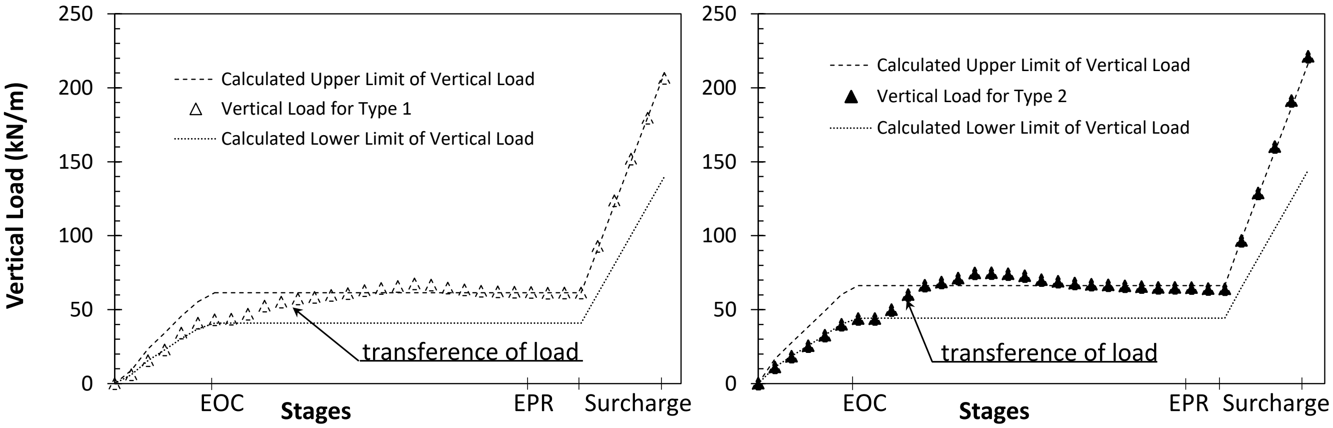

Figure 11. Comparison between the Calculated Upper and Lower Limit and Measured Vertical load above the pile caps for compaction Type 1 and Type 2.

3.4 Efficiency on Soil Arching

Efficiency corresponds to the portion of the backfill weight carried by the piles, in this case by the pile cap. With the use of basal reinforcement, the efficiency values start equal to the area replacement ratio and can vary up to 100% where the backfill weight is fully supported by the piles.

Figure 12 shows the efficiency *versus* settlements under the hydraulic platform for compaction Type 1 and Type 2. A prompt increase in efficiency was observed early in the platform release, and a slow decrease, with a tendency to remain stable. These values were later influenced by the surcharge application.

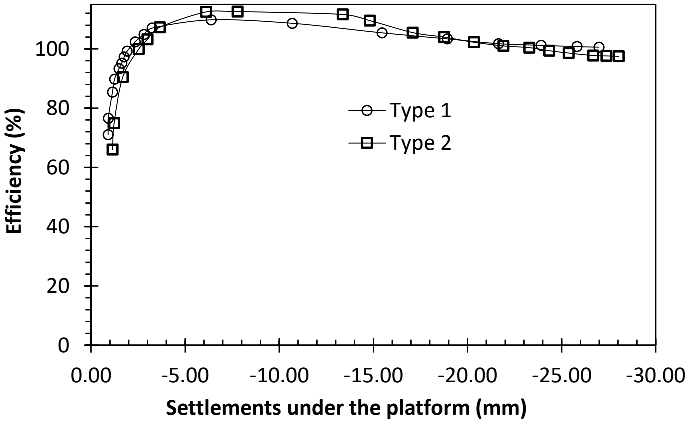

Figure 12. Calculated efficiency *versus* settlements measured under the platform.

4. SUMMARY AND CONCLUSIONS

Two large-scale physical model studies of GRPS construction under plane-strain condition are presented and discussed. The physical models construction sequence were the same, except for the two different types of hand-operated compactors were used: a vibrating plate and a vibratory tamper. Equivalent vertical stresses for the vibrating plate (referred to as the “light compactor”) were much lower than the corresponding value of the vibratory tamper (referred to as the “heavy compactor”). Those models were performed to monitor settlements, mobilized tensions along the reinforcement and the vertical stress at the interface between the pile caps and soil were monitored.

Combining vibratory plate and vibratory tamper achieves fewer settlements than using only the vibratory plate. Besides that, fewer differential settlements were observed for higher compaction of the soil structure. Comparison of the observed values of reinforcement load indicates agreement with the obtained results of settlements, more settlements lead to more reinforcement load for the less compacted soil structure.

Irrespective of the difference in compaction (heavy or light compaction), the efficiency on soil arching reach the maximum value and remain almost the same at the end of tests for both compaction Type 1 or Type 2. This can be explained by the use of very large size pile caps for the physical model.

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